A Sounding Rocket Experiment for the Chromospheric Lyman-Alpha Spectro-Polarimeter (CLASP)

Masahito Kubo

(National Astronomical observatory of Japan[*1]),

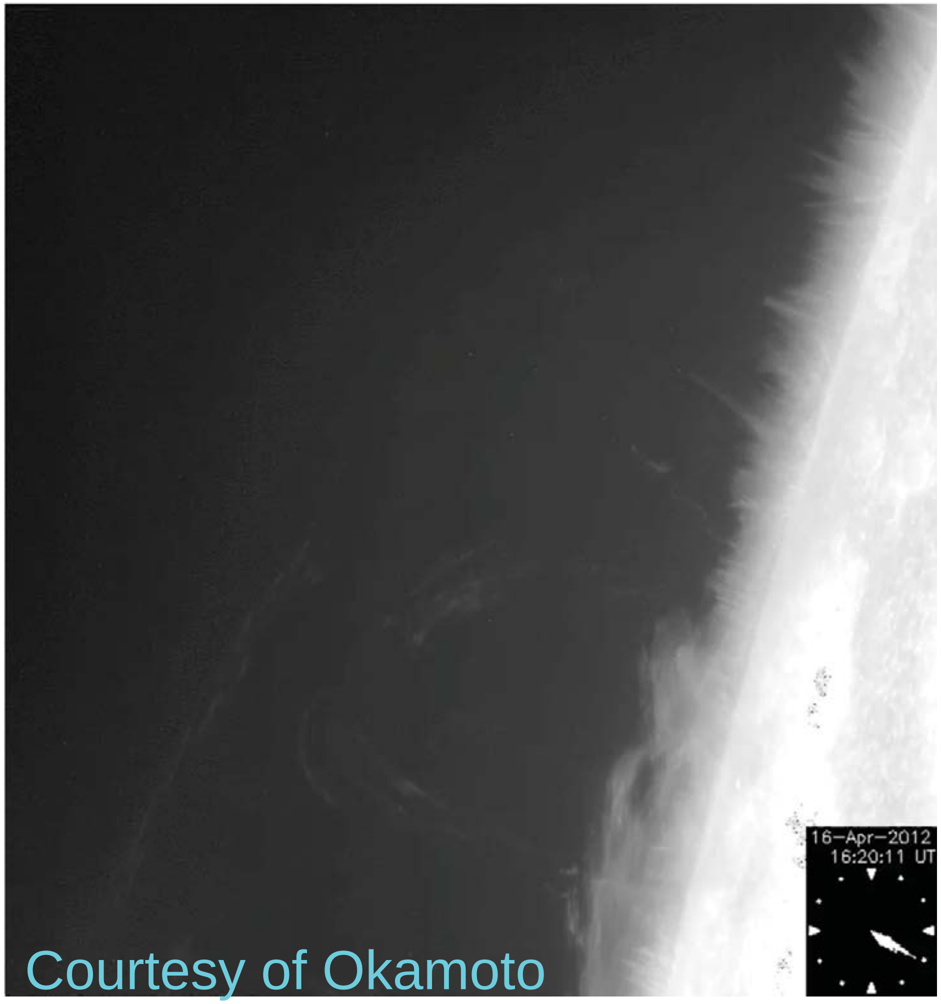
Kano, R.[1], Ishikawa, R.[1] Bando, T.[1], Narukage, N.[1],, Tsuneta, S.[3], Katsukawa, Y.[1], Ishikawa, S.[1], Suematsu, Y.[1], Hara, H.[1], Giono, G.[1], Shimizu, T.[3], Sakao, T.[3], Ichimoto, K.[4], Goto, M.[5] Winebarger, A.[2], Kobayashi, K.[2], Cirtain, J.[2], De Pontieu, B.[6], Casini, R.[7], Auchere, F.[8], Trujillo Bueno, J.[9], Manso Sainz, R.[9], Belluzzi, L.[9], Asensio Ramos, A.[9], Stepan, J.[10], Carlsson, M.[11]

(2) NASA Marshall Space Flight Center (3) ISAS/JAXA, (4) Kyoto University,
(5) National Institute for Fusion Science, (6) Lockheed Martin Solar & Astrophysics Lab,
(7) High Altitude Observatory, (8) Institut d'astrophysique spatiale, (9) Instituto de Astrofisica de Canarias, (10) Astronomical Institute of ASCR, (11) University of Oslo

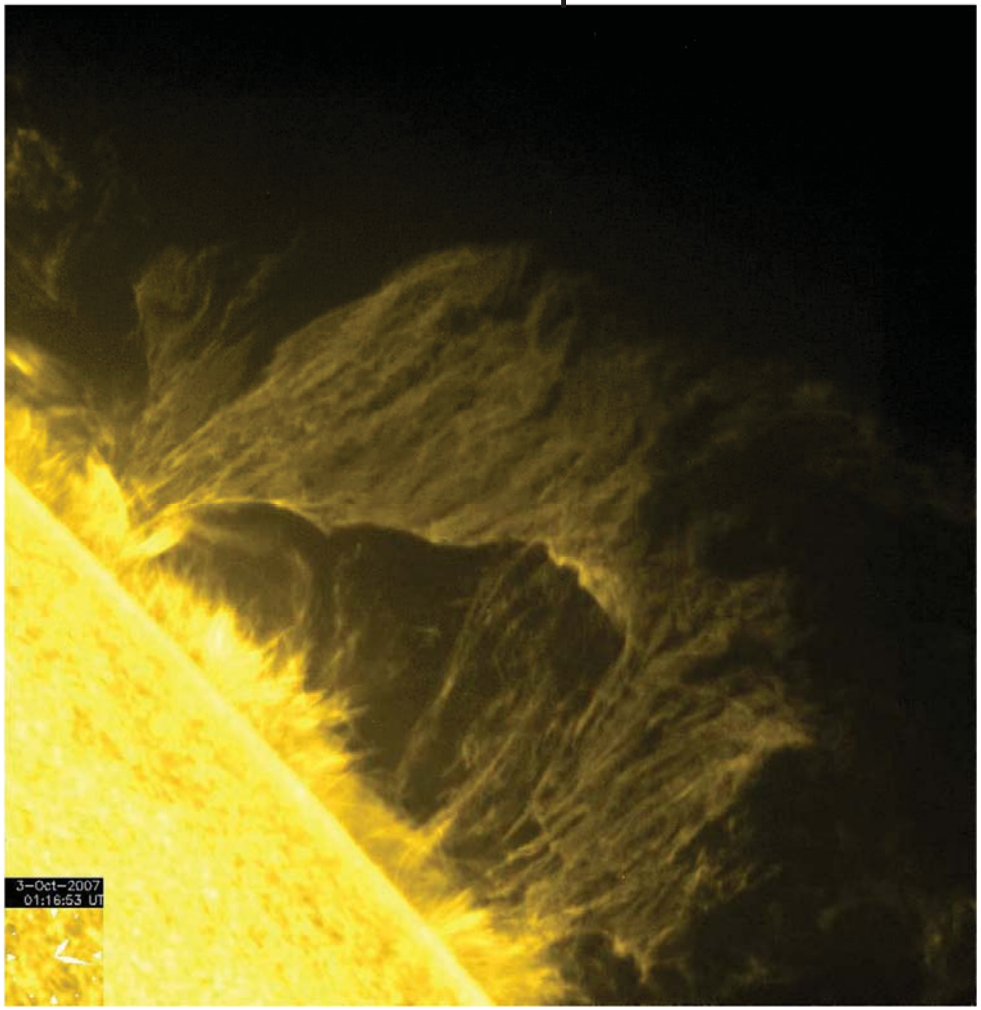
Chromospheric & Coronal Dynamics

Observations by *Hinode* revealed a variety of dynamic events in the chromosphere such as various types of jets and wave phenomena.

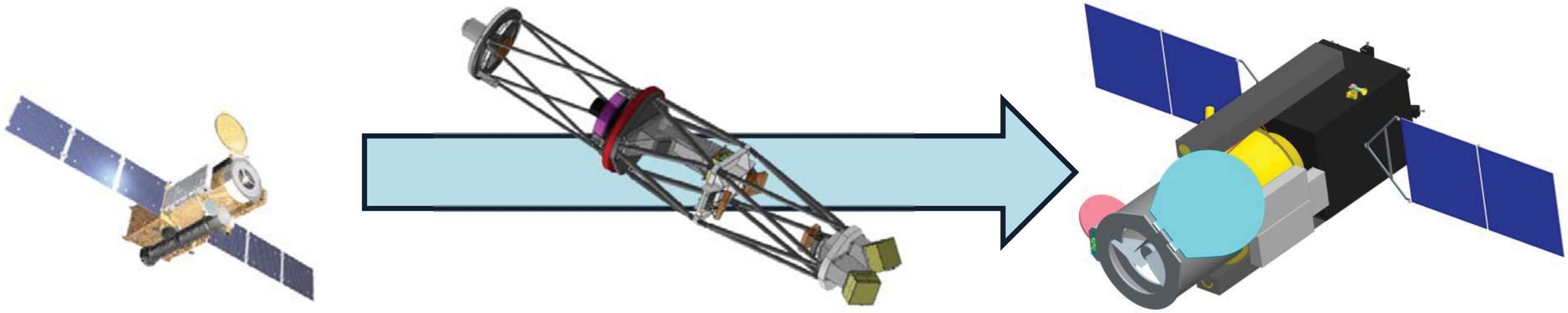
Flare & Coronal rains



Prominence & Spicules



Hinode to SOLAR-C through CLASP



Hinode (SOLAR-B, 2006 -) CLASP (2015) SOLAR-C (2020 -)

The exploration of magnetic field in the (upper) chromosphere is an important target for future solar telescopes, including SOLAR-C.

In the (upper) chromosphere and transition region:

- Magnetic field < 100G & Wide Doppler width → ~~Zeeman effect~~

→ Hanle effect (* magnetic field induced modification of the linear polarization due to scattering processes in spectral lines.)

- Non-LTE atmosphere

→3D radiative transfer tool (realistic 3D model atmosphere)

What's CLASP?

- The Chromospheric Lyman-alpha Spectro-polarimeter (CLASP) is to aim for **first high precision (0.1%) measurement of the linear polarization produced by scattering processes and the Hanle effect in the Lyman-alpha line (121.6nm).**

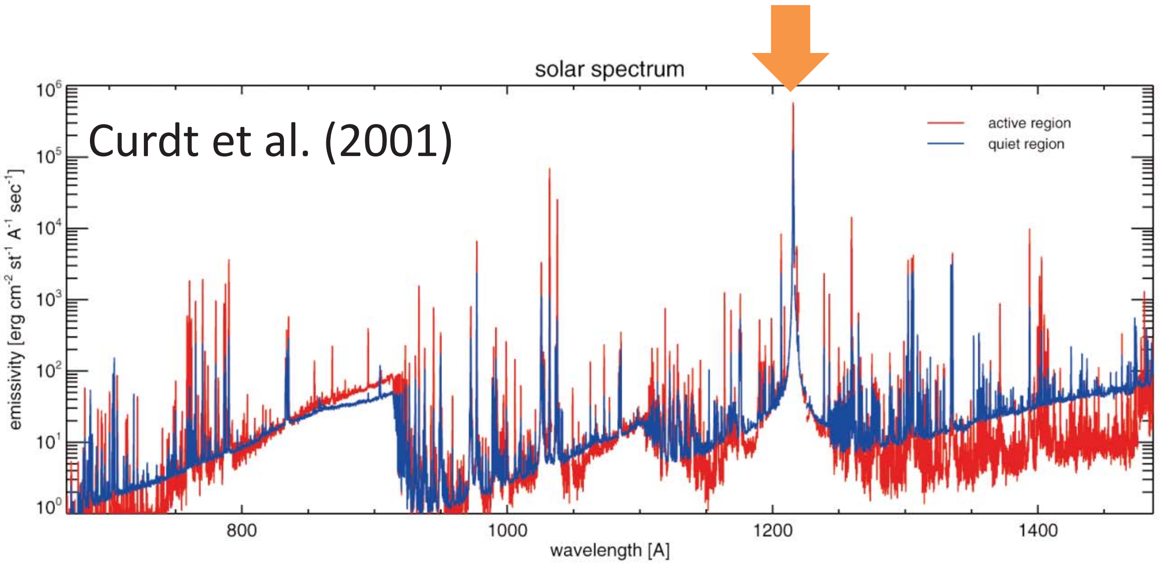
- CLASP proposal was accepted by NASA in 2012, and is planned to **fly in 2015.**

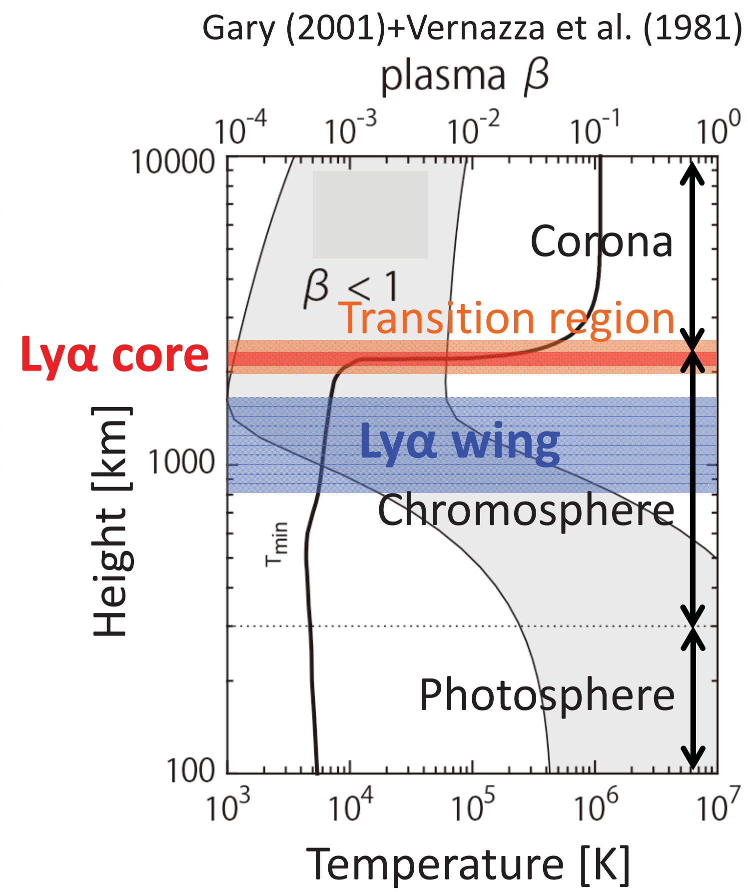
  ✓ ~ 5-minute observations during ballistic flight at White Sands in USA

- International collaborations (5 institutes in 12 countires) are to realize strong combination of powerful instrumentation, advanced numerical simulations, and theory of Hanle effect.

Spectropolarimetery in Ly-alpha

Ly-alpha (λ=121.6nm)



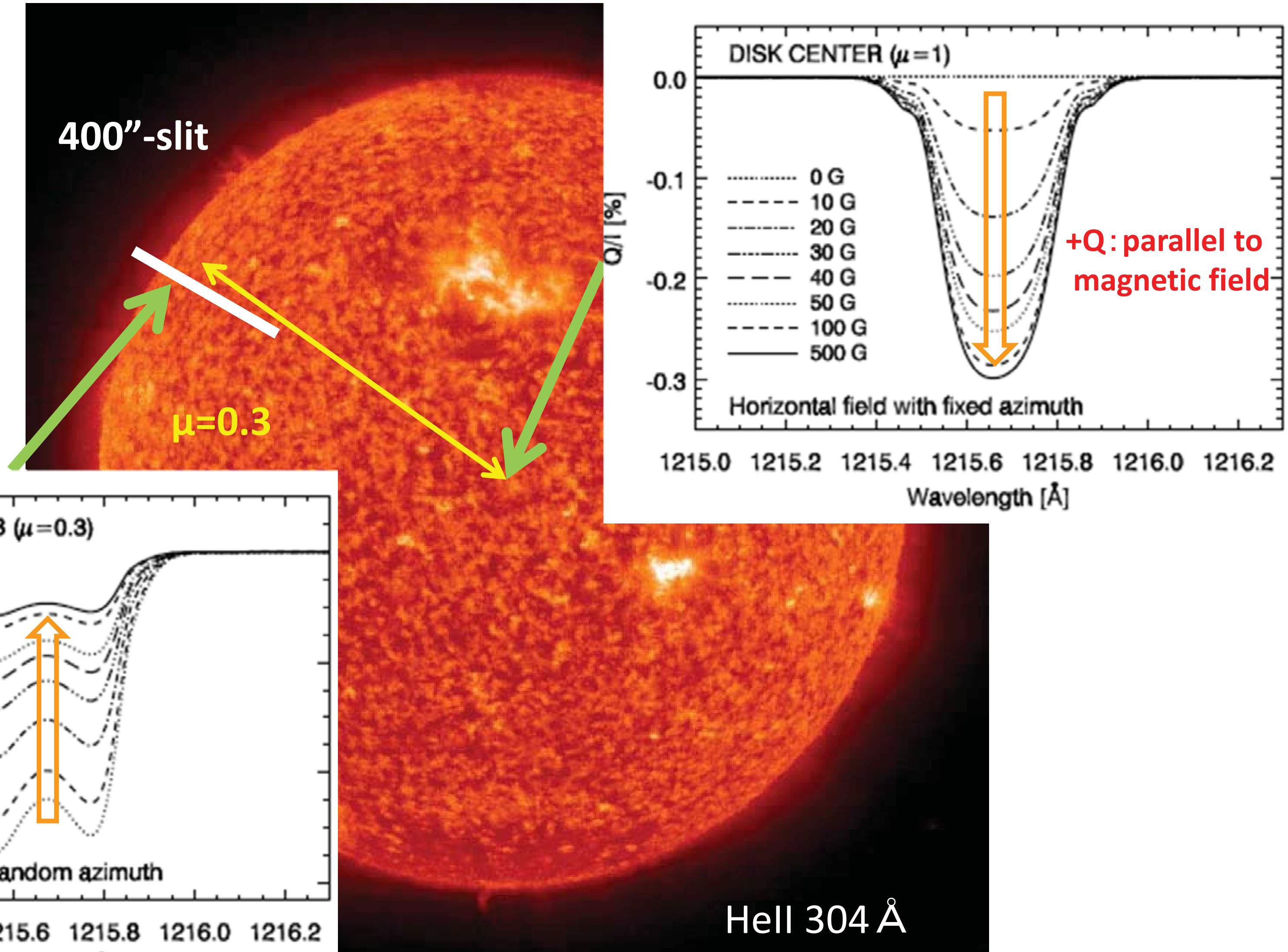


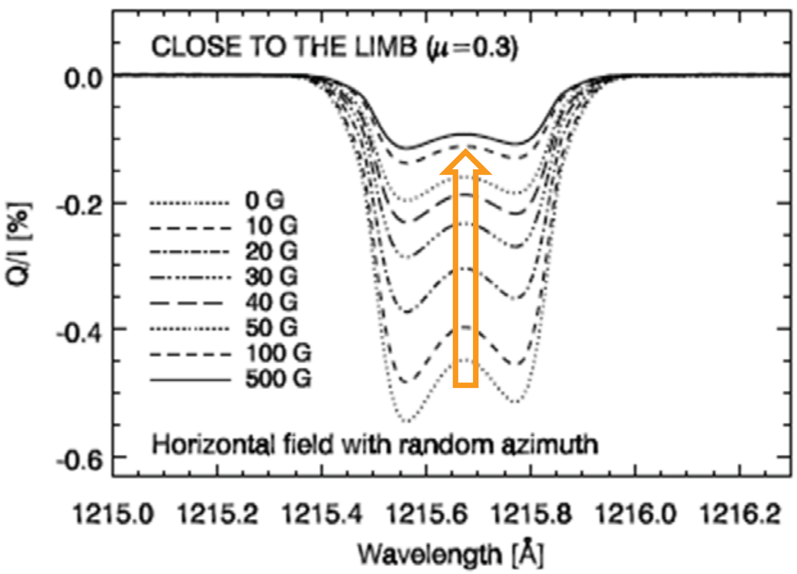
- Brightest in VUV range
  - Higher polarization sensitivity

- Emitted from the upper chromosphere and the transition region
  - Higher possibility to get magnetic information in the low β region (transition region!)

Expected polarization of Hanle effect in Lya

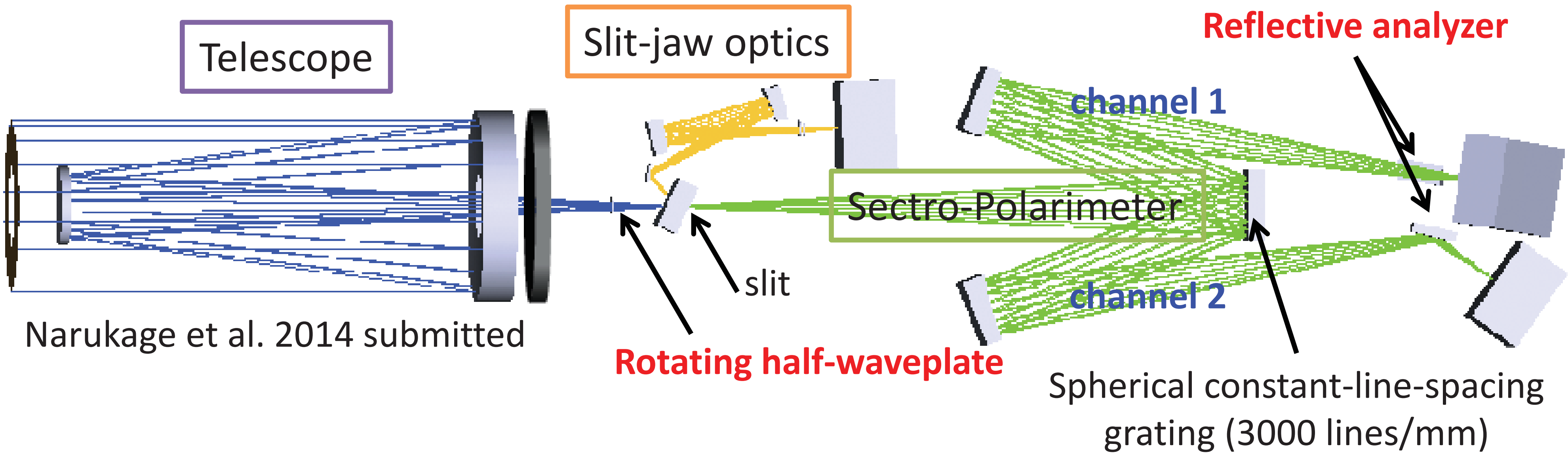
The slit of 400" can cover active areas in addition to QS.





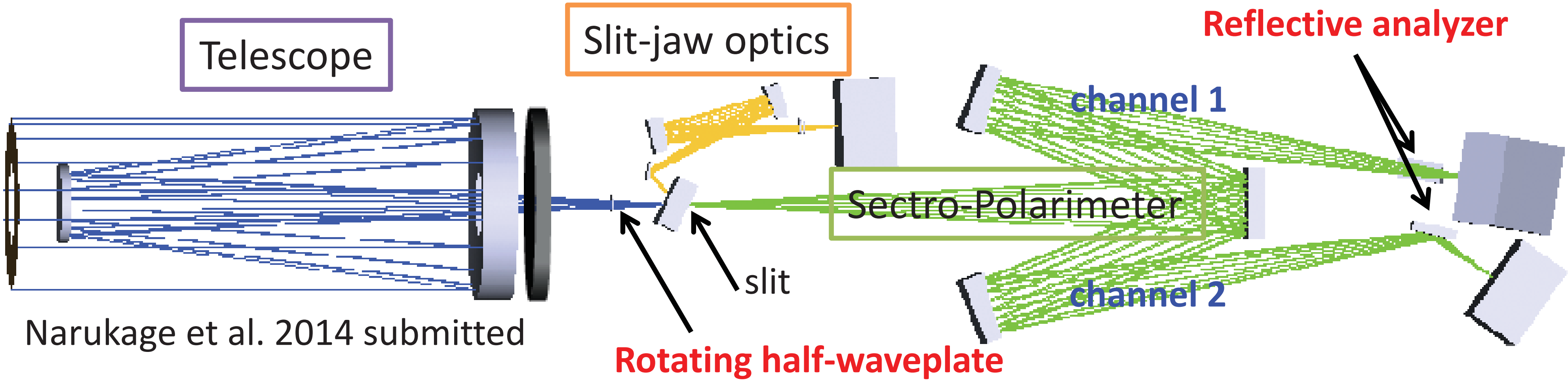
Trujillo Bueno et al. 2011, ApJ

CLASP Optical Layout



- The telescope and spectrograph designs were optimized together to provide the highest possible photon count in the Lyα line.
- Using diffracted beam with +/-1st order, two orthogonal linear polarizations are measured simultaneously with the rotating-half waveplate and reflective analyzers (polarizers).
- Solar images around the slit are monitored by the Slit-jaw optics.

CLASP Optical Layout



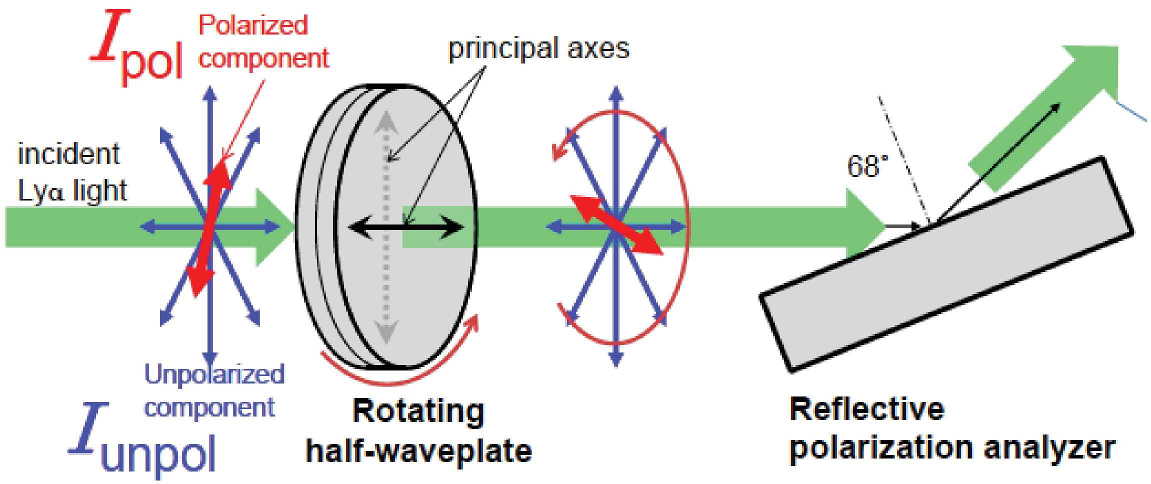
Narukage et al. 2014 submitted

Spectropolarimeter	
Wavelength resolution	0.013nm
Slit	1.45 arcsec (width), 400 arcsec (length)
Plate scale	1.11 arcsec/pixel (space), 0.0048nm/pixel (wavelength)
Wavelength coverage	121.567nm ± 0.6nm

Telescope	
Aperture	ϕ270 mm
Eff. Focal length	2614 mm (F/9.68)
Visible light rejection	"Cold Mirror" coating on primary mirror

Slit-jaw Optics	
Wavelength	Lyα (10nm FWHM width filter)
Plate scale	1.03 arcsec/pixel
FOV	527 x 527 arcsec

Polarization Measurements by CLASP



- We successfully develop:
  - ✓ Half waveplate for Ly-alpha (Ishikawa et al. 2013).
  - ✓ Polarization analyzers having high polarization efficiency (γ=Rs/Rp = 98.9). Its high reflectivity multilayer coatings is based on the design by Bridou et al. (2011).
- Their polarization properties are confirmed by our experiment in a synchrotron facility in Japan.

Requirements & Control of Polarization

Requirements on polarization for CLASP	
Polarization sensitivity (line core)	0.1 % (121.57 ± 0.02 nm)
Polarization sensitivity (line wing)	0.5 % (>±0.05 nm from line core)
Polarization amplitude error	10 %
Angle error of linear polarization	2 degree

Strategy for Polarization Error Control (Ishikawa et al. 2014):

1. Measure the throughput and the polarization properties of each optical component in the Lyman-α line.

2. Perform polarization calibration of the spectro-polarimeter after alignment. The spurious polarization caused by the telescope is negligibly small.

3. Verify the polarization sensitivity using the in-flight calibration data acquired by observing the disk center.

Example: Error Budget for Spurious Polarization

- Non-calibrated items are considered.

Ishikawa et al. 2014

Cause of error	**error** (1σ)	
Photon noise (~10” summing along slit) at Ly-a center	0.019%	Random noise
Readout noise of CCD cameras	0.007%	
Fluctuation of exposure durations	10^{-4}%	
Time variation of source intensity	<0.018%†	*dI/dt*
Intensity variation caused by pointing jitter	<0.023%†	
Image shift from waveplate rotation	~0%	
Off-axis incidence with 200′′	~10^{-4}%	Induced by telescope
Non-uniformity of coating on primary mirror	10^{-3}%	
Error in polarization calibration	0.017%	
RSS	**<0.039%**	

†: These values are the case for the single channel demodulation, and can be reduced by dual channel modulations.

Integration of Flight Items

- Optical alignment of telescope and spectropolarimeter independently with the visible light as much as possible.
  *VL grating that has a diffraction angle same as Ly-alpha is prepared.

- Sunlight test is to verify the stray light in the visible light wavelength after the connection of the telescope to the spectropolarimeter.

Done

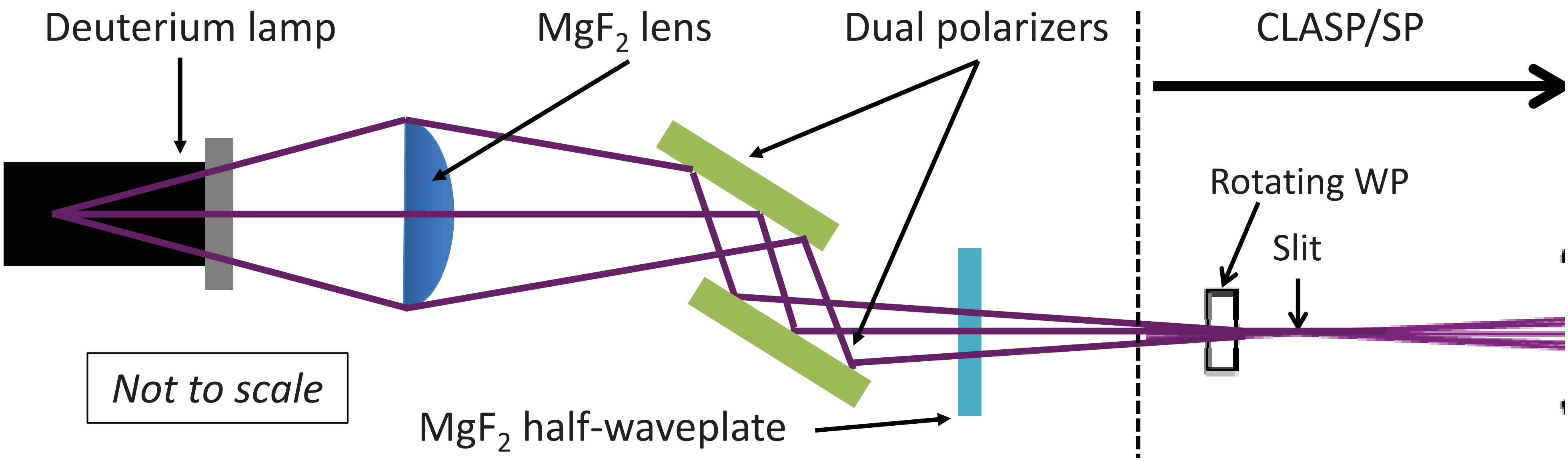
- Optical alignment of spectropolarimeter with the Ly-alpha light in the vacuum (rotation of grating, CCD focus adjustment).

- Polarization calibration with the Ly-alpha light in the vacuum.

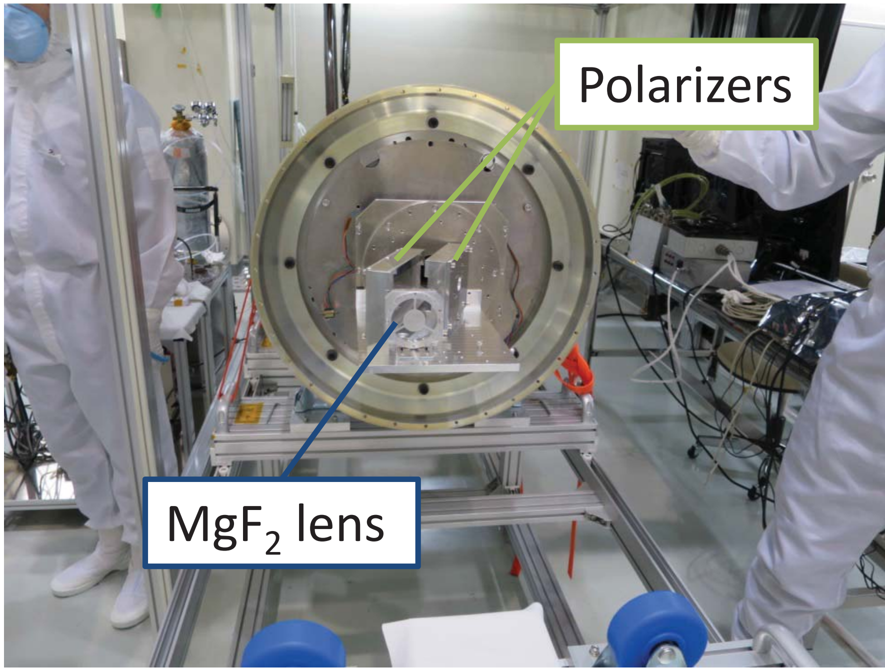
- Final integration of the telescope to the spectropolarimeter

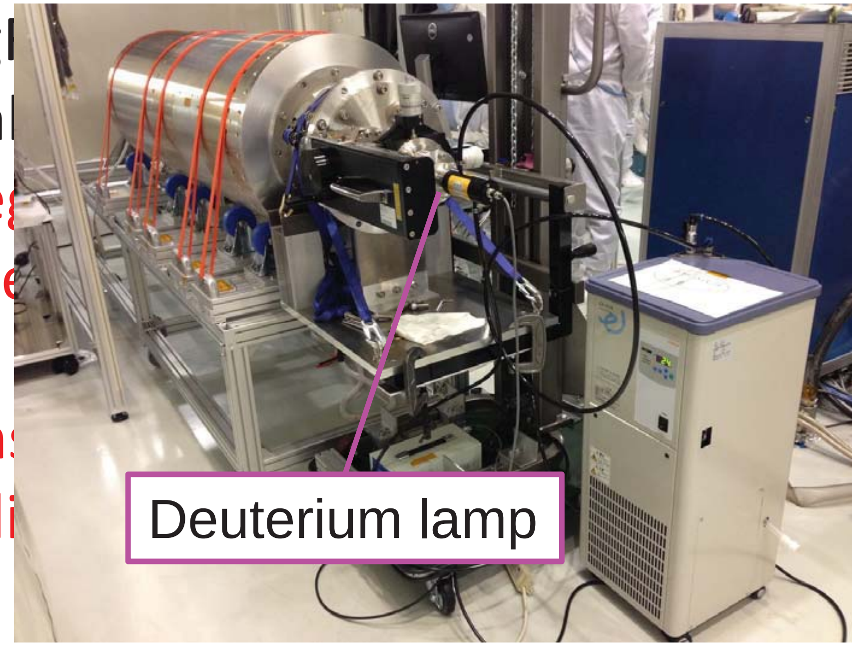
CLASP UV Light Source

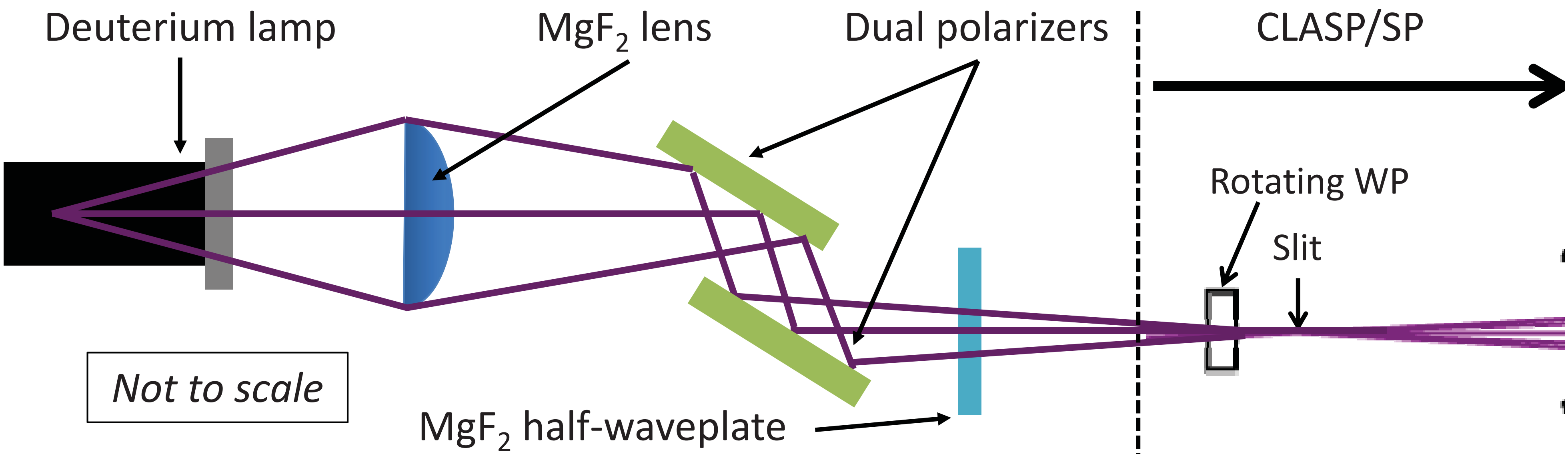
- The deuterium lamp with an MgF2 lens provides a converging beam with an *F* number identical to that of the CLASP telescope.
- Linearly polarized light with a degree of polarization of >99.9 % is produced by dual polarizers (same as CLASP flight ones) at Brewster's angle.
- Four different linear polarizations (0º,45º,90º,135º) can be feed to CLASP/SP by rotating the entire light source with dual polarizer or rotating the half-waveplate



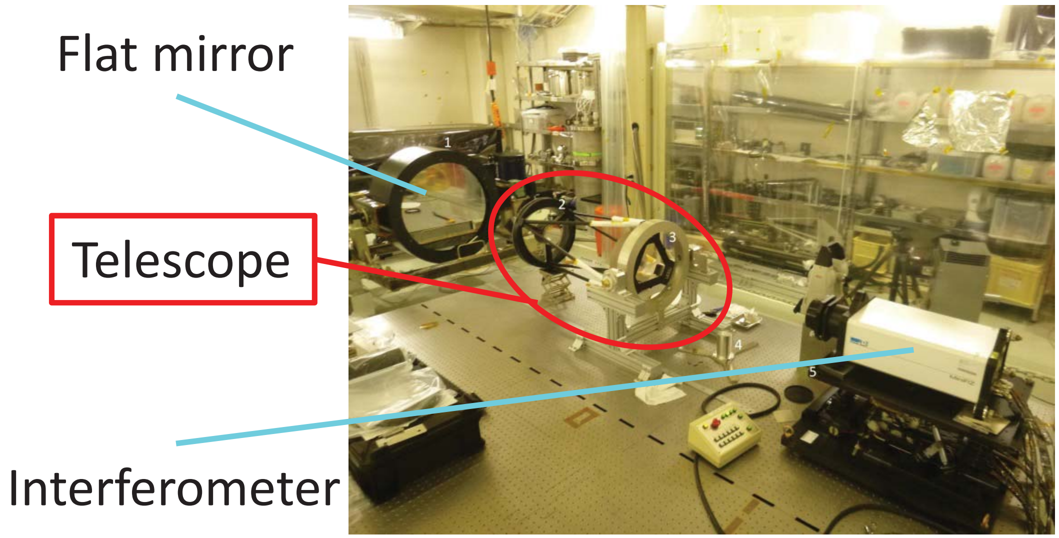
CLASP UV Light Source

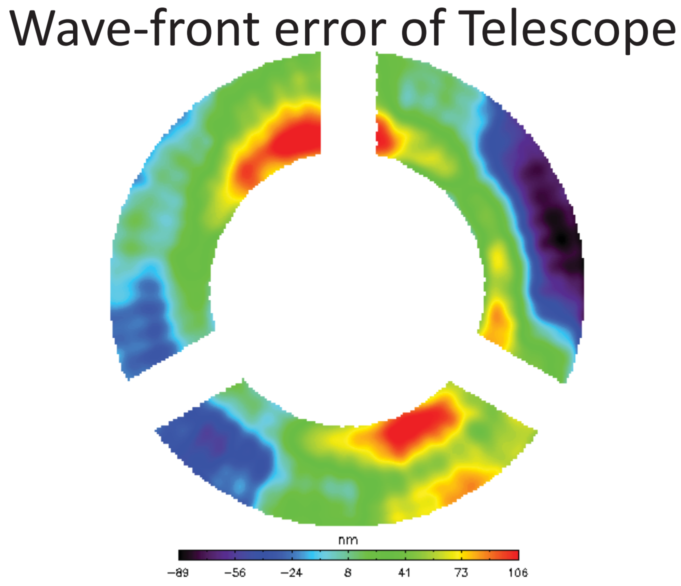


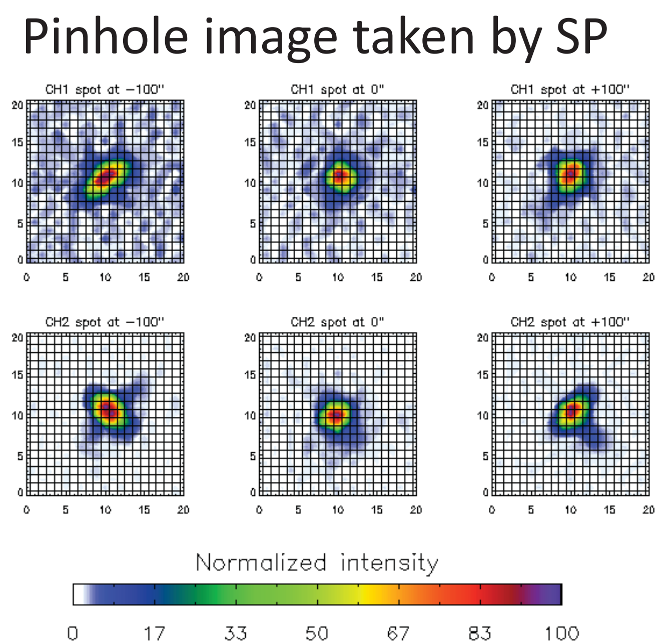




Optical Alignment with Visible Light





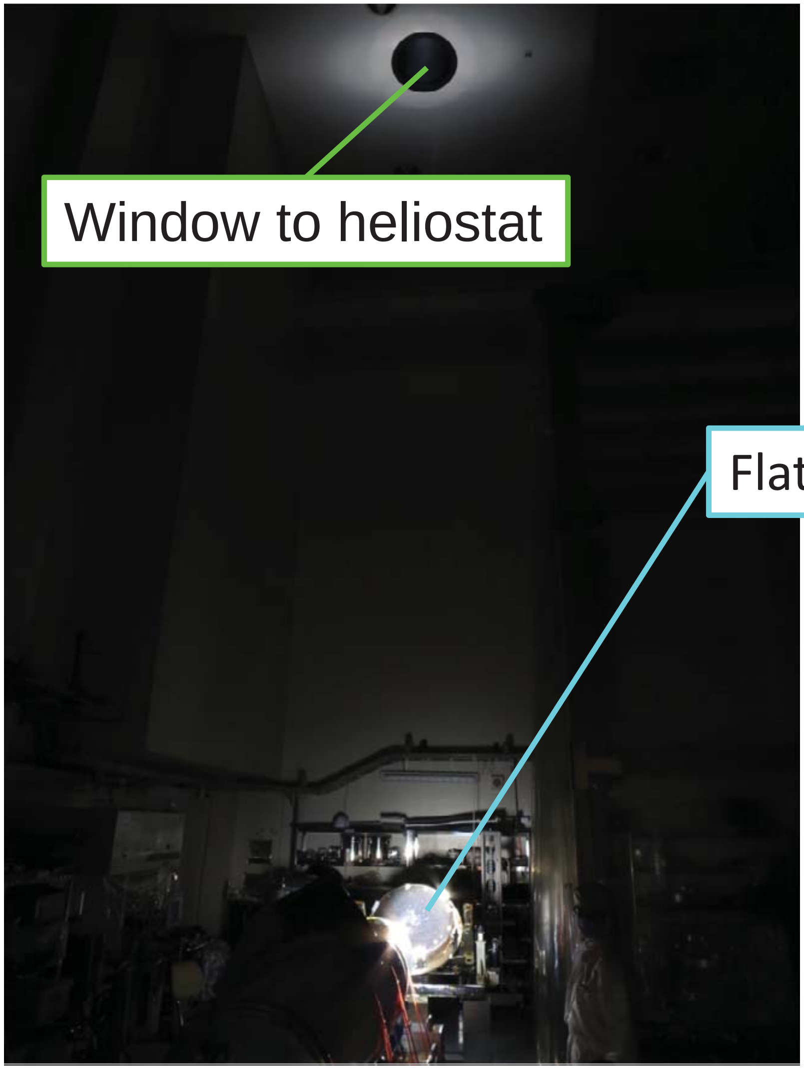


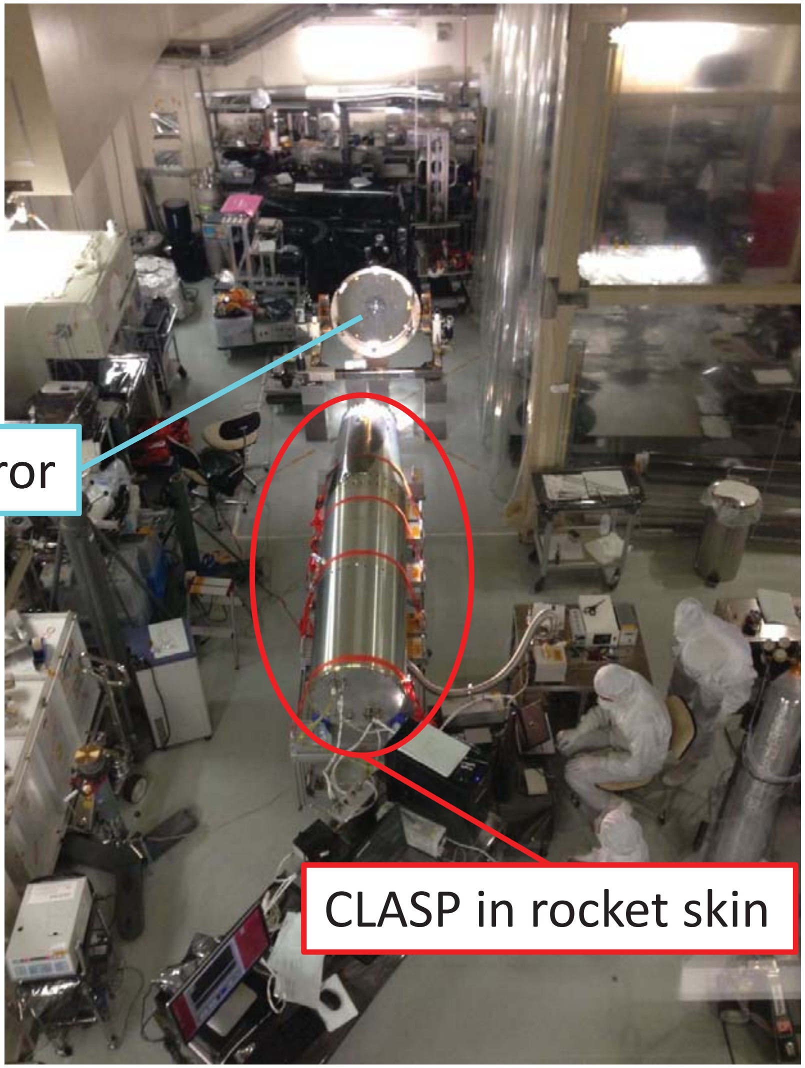
The optical alignment of telescope and SP are successfully done to meet out requirements.

- ✓ Tel: Wave-front error (interferometer)
- ✓ SP: Size of Pinhole image

Sunlight Test

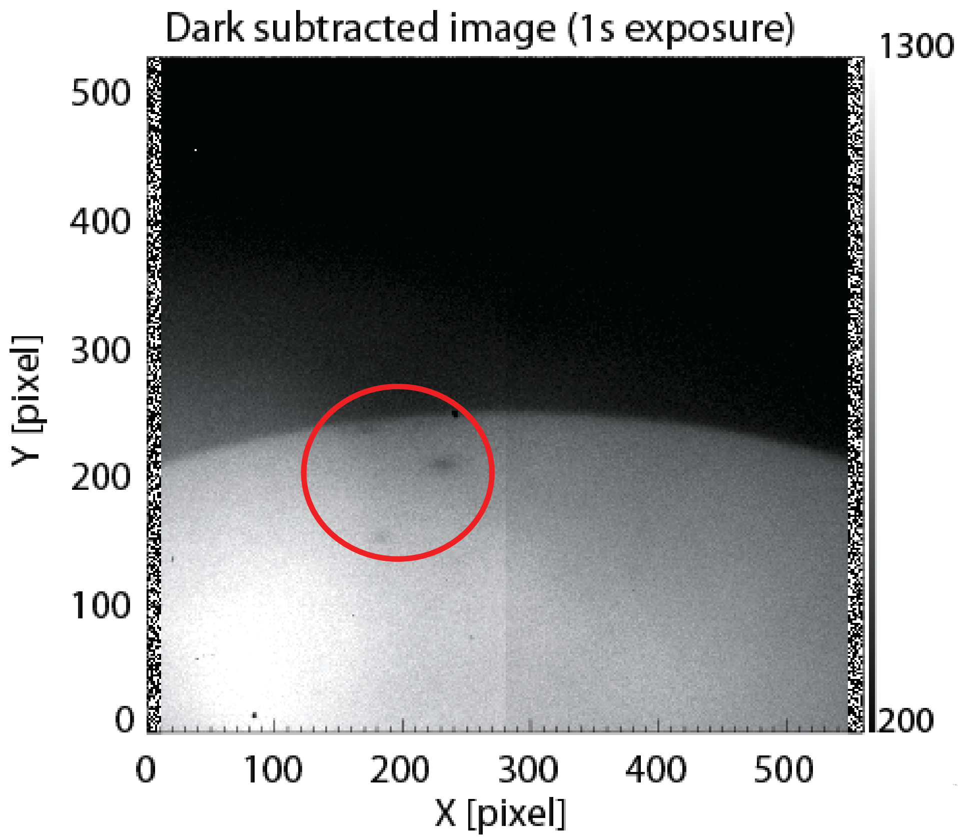
The stray light in the visible light wavelength has been measured, and we are verifying data carefully.

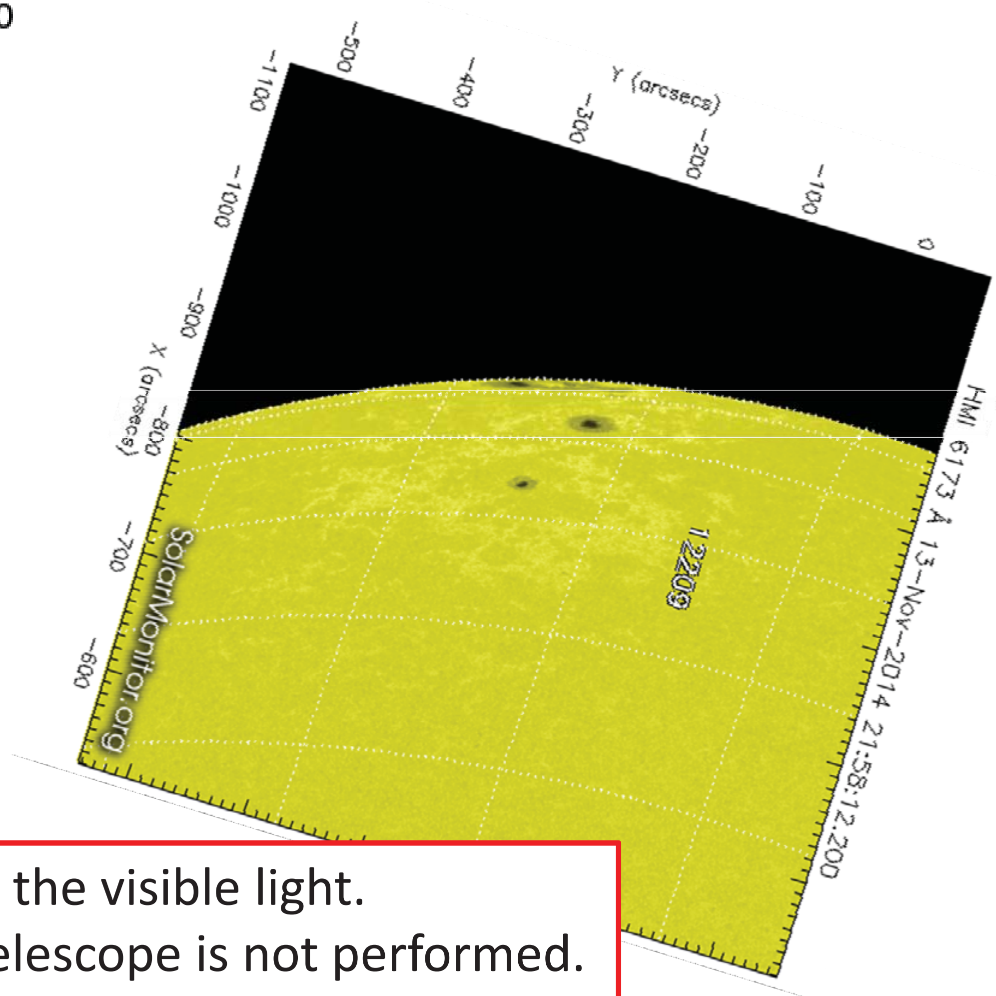




Instrumental First Light

Three sunspots in AR12209 were observed by the Slit-jaw optics.



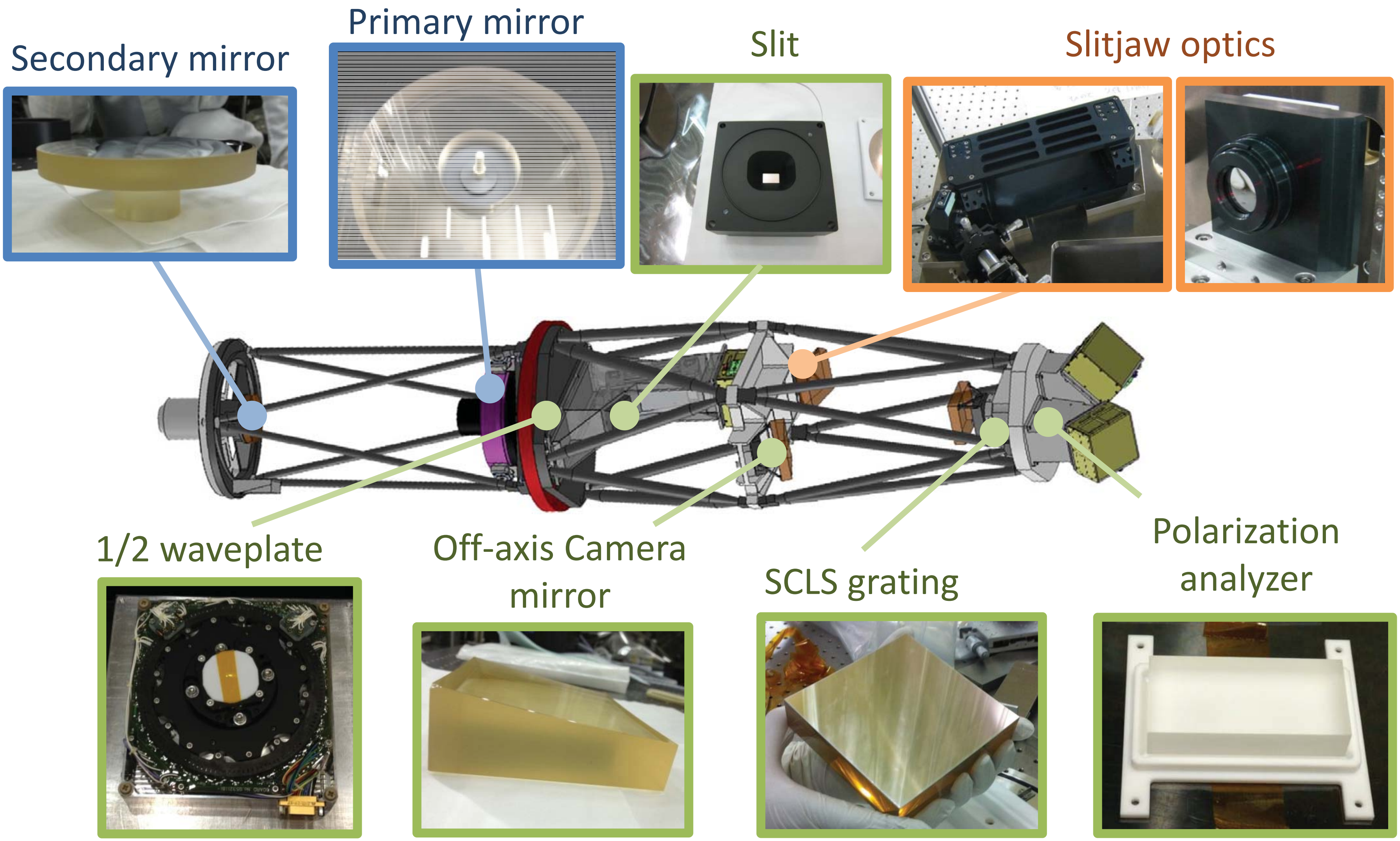


- Non-flight filter is used for the visible light.
- Focus adjustment of the telescope is not performed.
- Seeing condition at NAOJ is not good.

Thank you!

Appendix

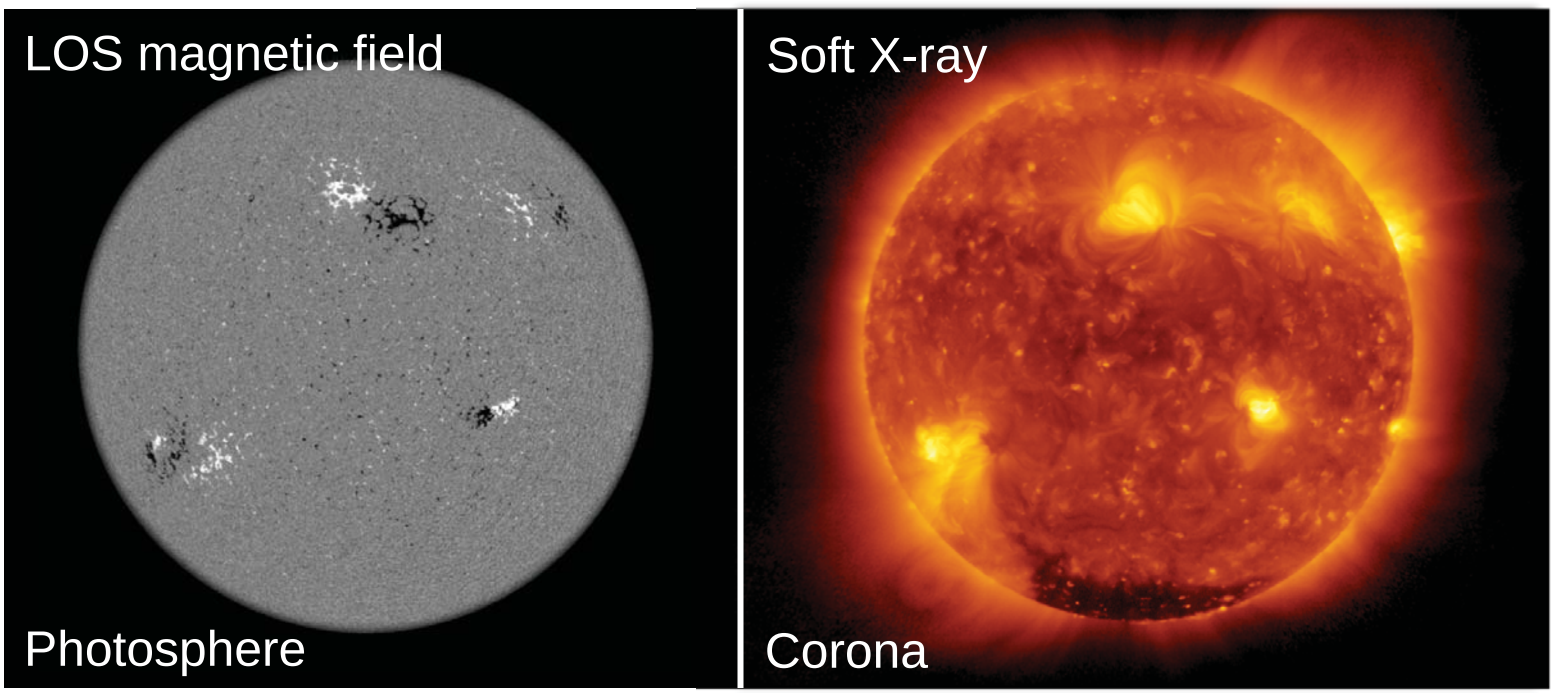
Flight Instruments



Science Requirements

Observable	Requirement
Target	On-disk, away from disk center Quiet Sun and other structures

- In terms of coronal heating issues, QS magnetic field in the chromosphere would be more important than AR.
- Measurements of QS magnetic fields are more challenging (new frontier).



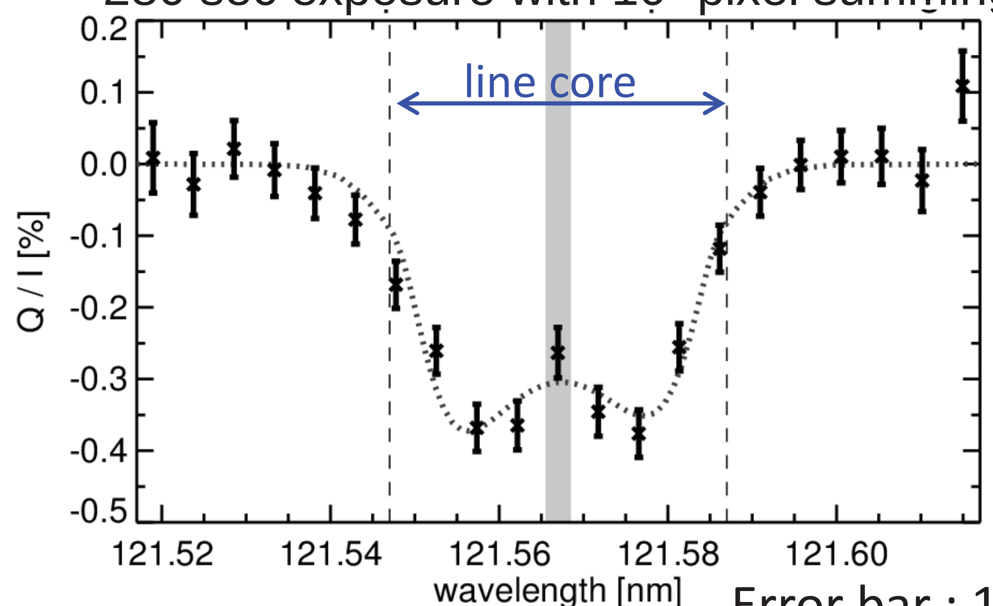
Science Requirements

Observable	Requirement
Target	On-disk, away from disk center Quiet Sun and other structures
Polarization sensitivity	0.1% (line core), 0.5% (line wing)
Spectroscopic resolution	0.01nm
Spectral window	> ±0.05nm
Spatial resolution	< 10 arcsec
Temporal resolution	< 5 minutes

With the integration time of 280 sec and 10” summing, polarization sensitivity of 0.1% (3σ) will be achieved.

*Polarization error budget will be in Ishikawa-san’s talk tomorrow.

280 sec exposure with 10” pixel summing



Error bar : 1σ

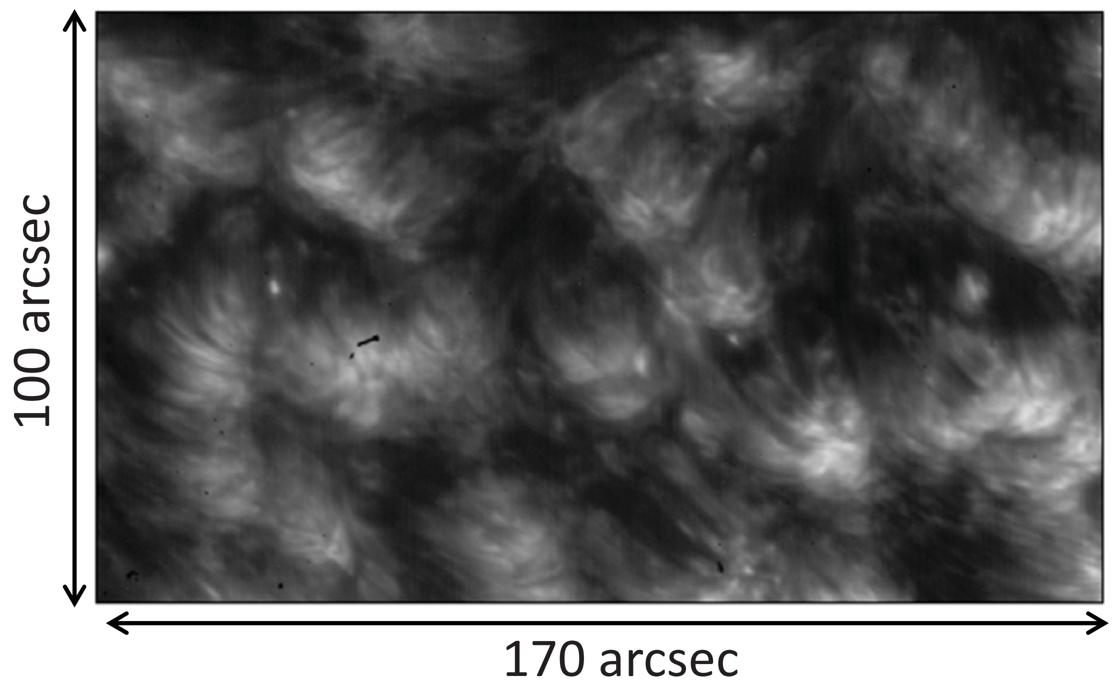
Science Requirements

Observable	Requirement
Target	On-disk, away from disk center Quiet Sun and other structures
Polarization sensitivity	0.1% (line core), 0.5% (line wing)
Spectroscopic resolution	0.01nm
Spectral window	> ±0.05nm
Spatial resolution	< 10 arcsec
Temporal resolution	< 5 minutes

10 arcsec resolution

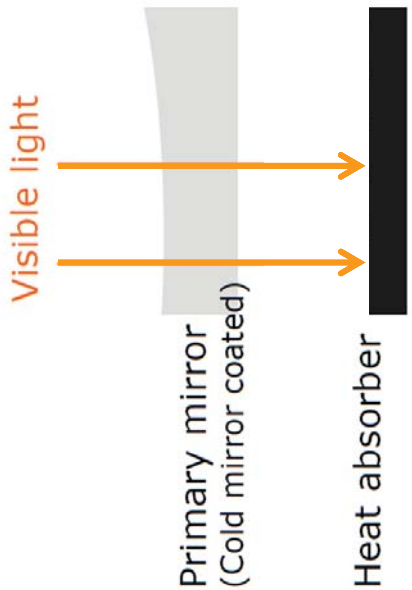
→ Magnetic field structures at supergranular scales

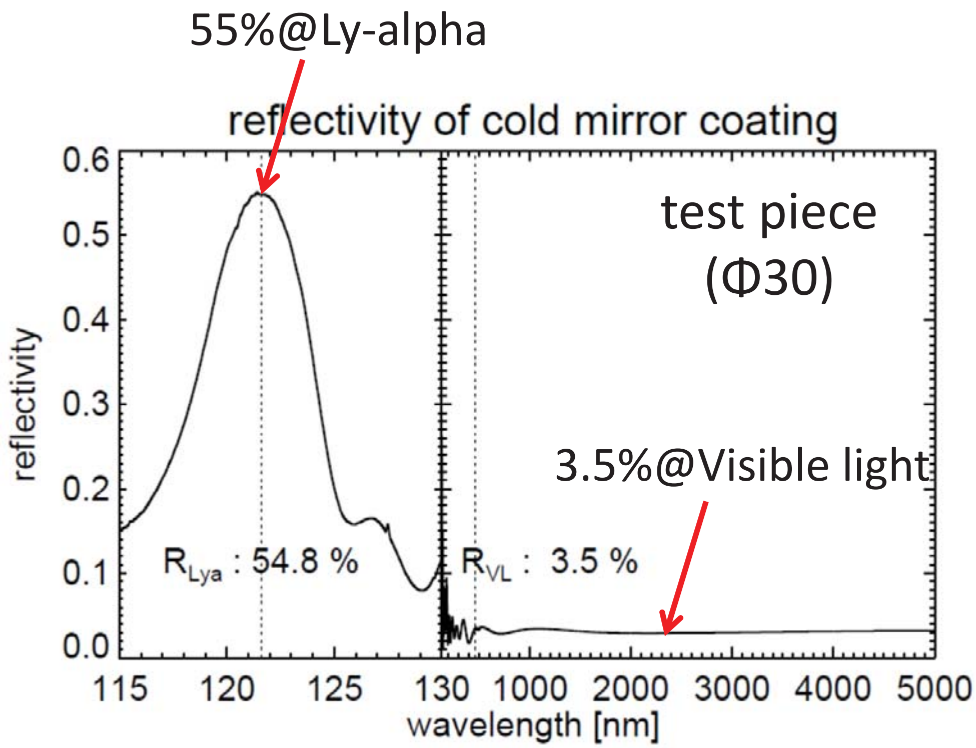
Ly-alpha image taken with VAULT (courtesy of Dr. Angelos Vourlidas.)



Cold Mirror Coating on Primary Mirror

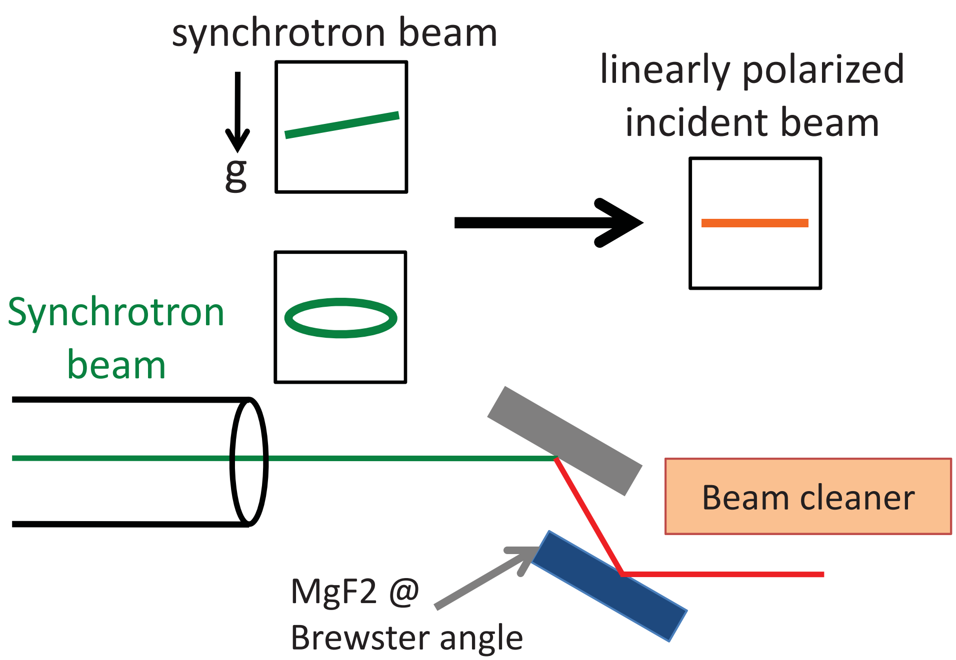
- Cold mirror coating on primary mirror dumps heat and removes visible light contamination.

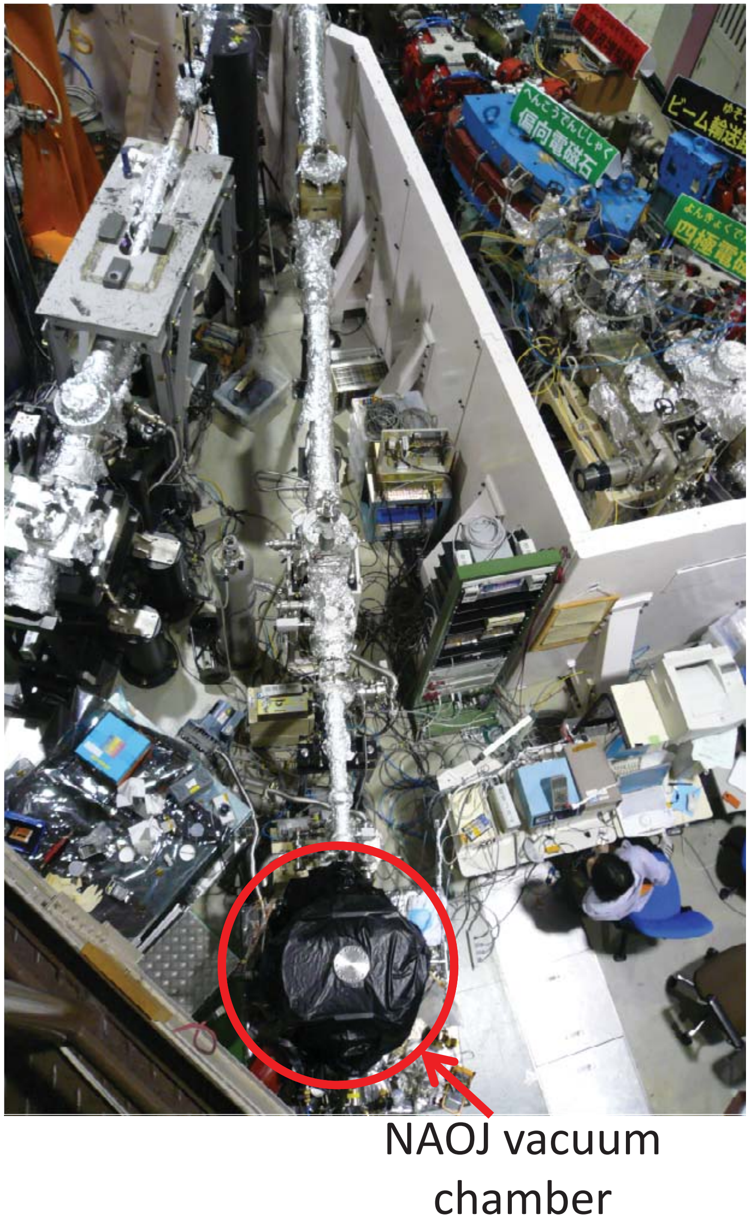




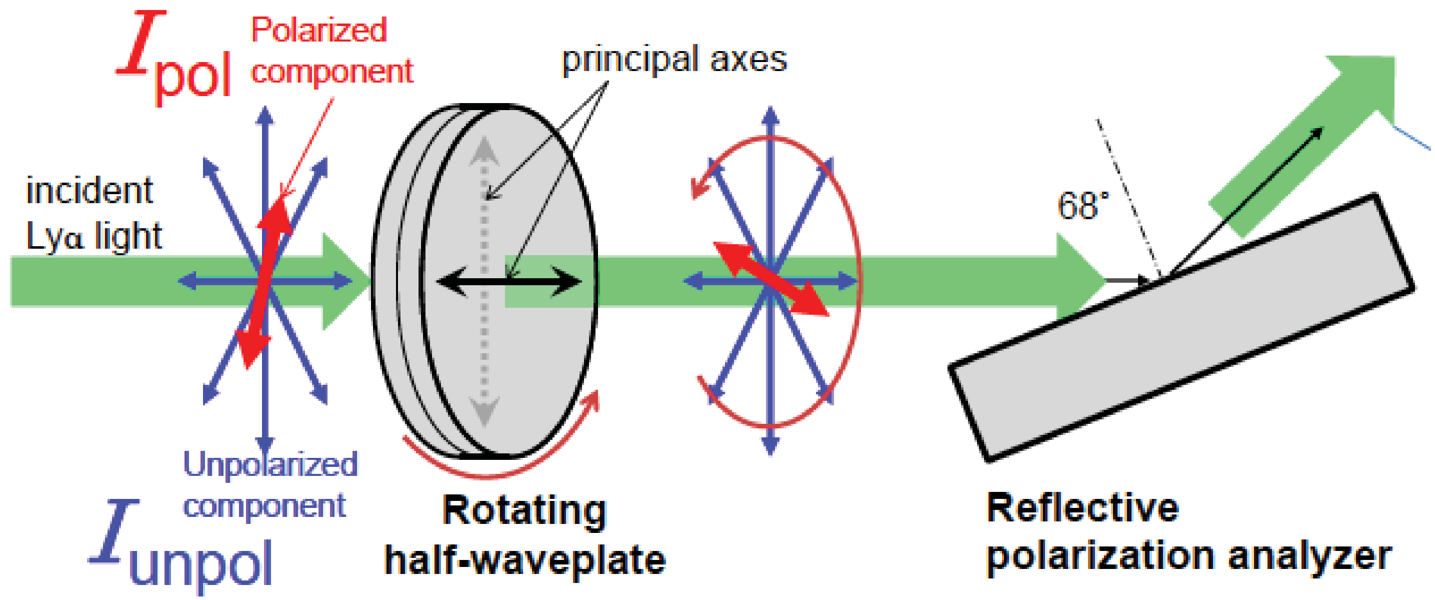
Development of Optical Elements for Ly-alpha

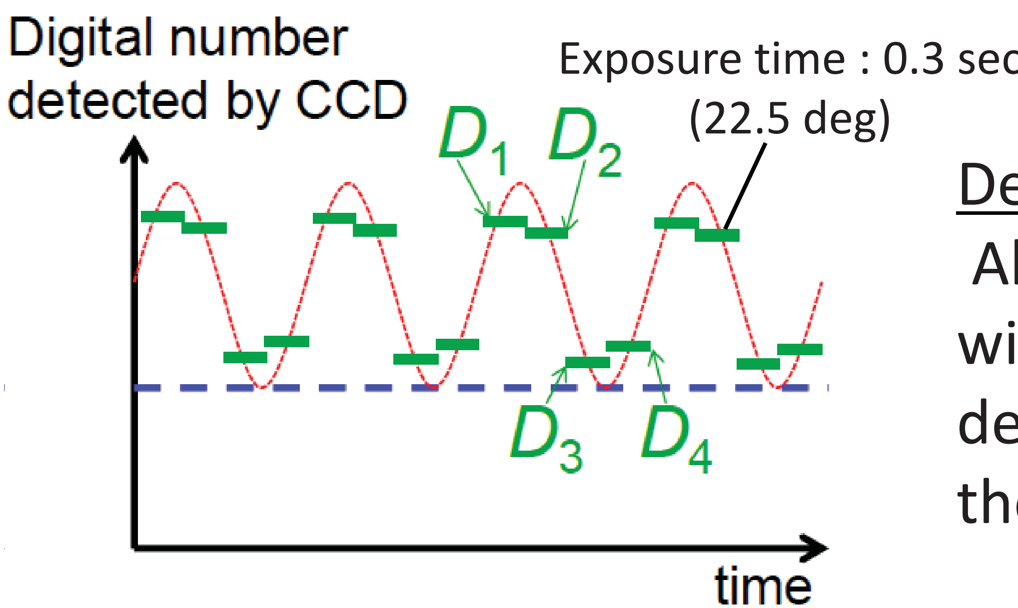
- UltraViolet Synchrotron OR-bital Radiation Facility (UVSOR) at the institute for Molecular Sciences (partner institute of NAOJ)
  - More than 4 weeks per year are allocated since 2009 FY.
  - All optical components are tested and evaluated with Ly-alpha.





Modulation & Demodulation

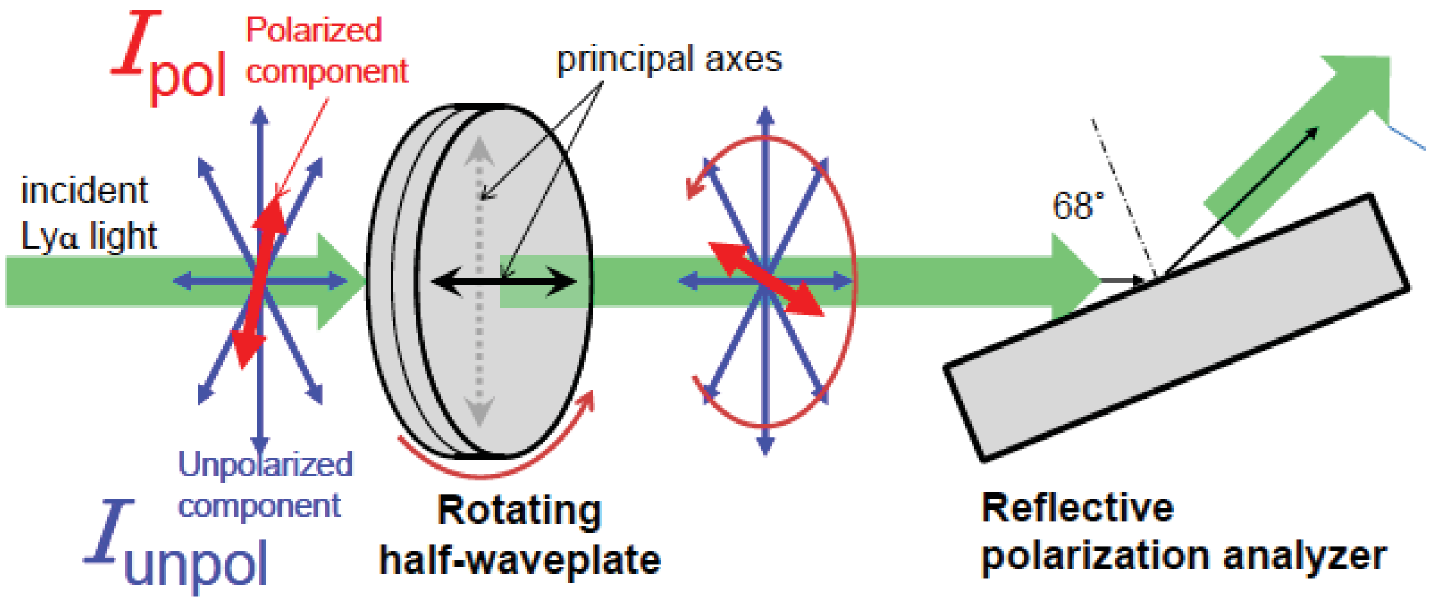


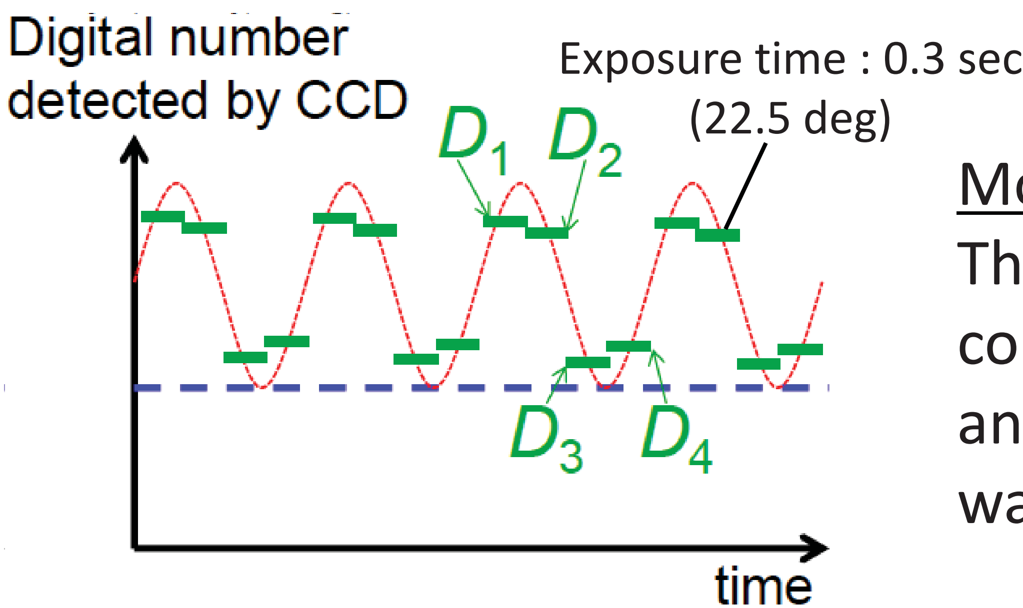


<u>Demodulation</u>

All the raw data are returned without onboard processing, and demodulation will be done on the ground using all flight data.

Polarization Measurements by CLASP



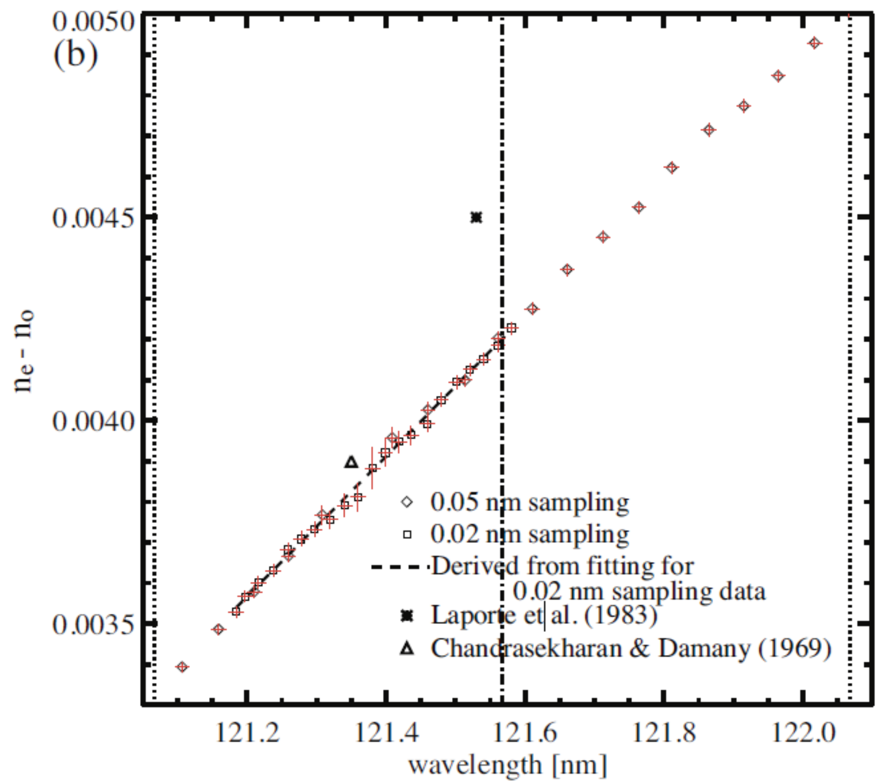


<u>Modulation</u>

The waveplate rotates at a constant rate (4.8 sec/rotation) and acquiring 16 exposures per waveplate rotation.

Half-waveplate for Ly-alpha

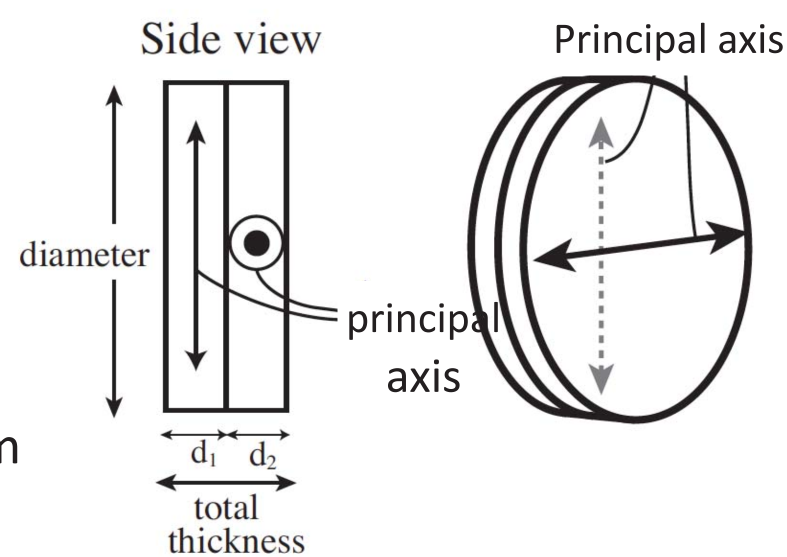
- Two stacked MgF_2 plates with slightly different thicknesses and their principal axes rotated by 90° from each other.



Retardation $\delta = \dfrac{2\pi(n_e - n_o)(d_1 - d_2)}{\lambda}$

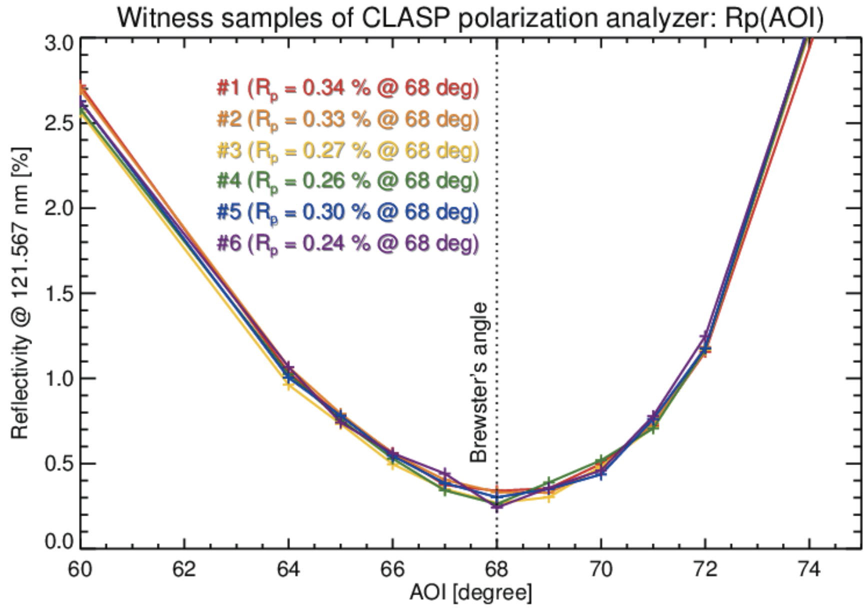
Measured value used to determined the thickness difference for flight WP with δ=180° .

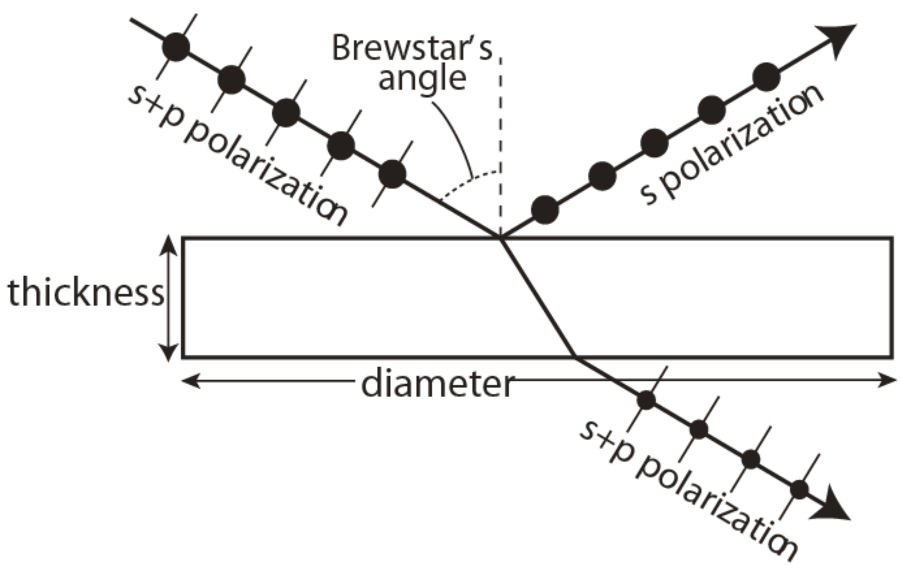
ne − no = 0.004195 ± 0.000036 at 121.57 nm (Ishikawa et al. 2013)

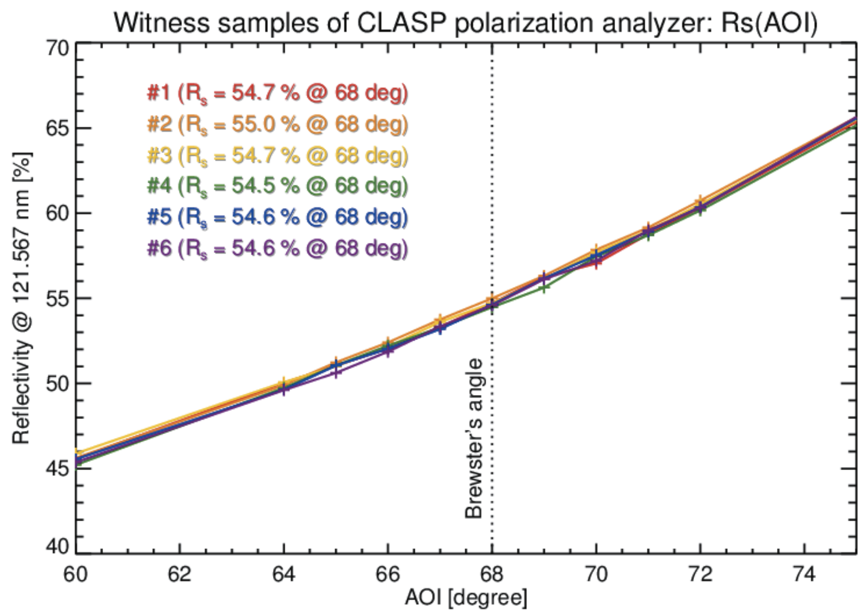


Reflective Polarization Analyzer for Ly-alpha

- High reflectivity multilayer coatings based on the design by Bridou et al. (2011) to have high polarization efficiency ($\gamma=R_s/R_p$).

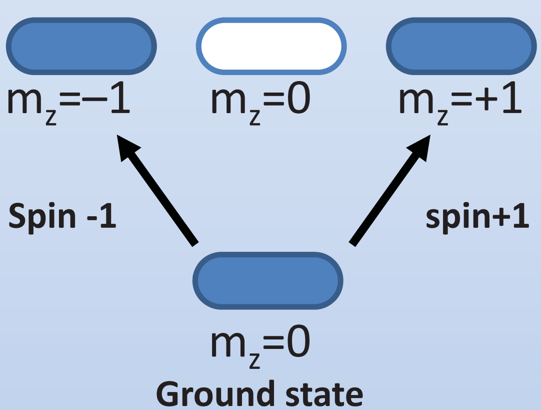


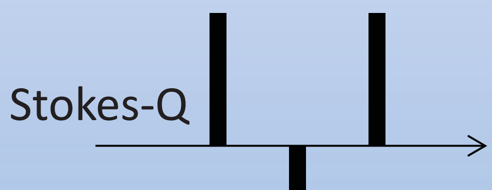




Origin of linear polarization in scattered lights

STEP1:
Population imbalance between atomic sublevels induced by **anisotropic radiation** illuminating atom.





Polarizations remain even after cancellation.

STEP2:
Quantum coherency by rotation of quantization axes.

STEP3
Magnetic fields dephase and decrease the coherence (Hanle effect). It is a competition between Larmor motion and de-escitation.

$$\boxed{\frac{1}{\omega_0} \quad \text{vs.} \quad \frac{1}{A}}$$

time scale to change coherency

time scale for de-excitation